

A MERLIN Observation of PSR B1951+32 and its associated Plerion

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ABSTRACT

In an investigative 16 hour L band observation using the MERLIN radio interferometric array, we have resolved both the pulsar PSR B1951+32 and structure within the flat spectral radio continuum region, believed to be the synchrotron nebula associated with the interaction of the pulsar and its ‘host’ supernova remnant CTB 80. The extended structure we see, significant at $\sim 4.5 \sigma$, is of dimensions $2.5'' \times 0.75''$, and suggests a sharp bow shaped arc of shocked emission, which is correlated with similar structure observed in lower resolution radio maps and X-ray images. Using this MERLIN data as a new astrometric reference for other multiwavelength data we can place the pulsar at one edge of the HST reported optical synchrotron knot, ruling out previous suggested optical counterparts, and allowing an elementary analysis of the optical synchrotron emission which appears to trail the pulsar. The latter is possibly a consequence of pulsar wind replenishment, and we suggest that the knot is a result of magnetohydrodynamic (MHD) instabilities. These being so, it suggests a dynamical nature to the optical knot, which will require high resolution optical observations to confirm.

Subject headings: ISM: individual (CTB 80) — ISM: supernova remnants — pulsars: individual (PSR B1951+32) — stars:neutron — radiation mechanisms: non-thermal

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1. Introduction

Recent subarcsecond Hubble Space Telescope (HST) & Chandra observations of the inner Crab Nebula have yielded evidence of dynamic activity in close proximity to the pulsar with various shocks and ‘wisps’ evolving in terms of position, morphology and luminosity over timescales of days to weeks, implying local velocities of order $0.7c$ (Hester et al. 1996; Weisskopf et al. 2000). Observations in the radio using the Very Large Array (VLA) show evidence for similar time-varying morphological changes within the nebula but at scales of order 1” (Bietenholz et al. 2001).

Such multiwavelength observations challenge our understanding of these pulsar/plerion/supernova remnant (SNR) associations. Considering the Crab Nebula, the estimated current rate of particle injection derived via nebular X-ray luminosity differs markedly from the historical average rate determined from the radio emitting particles (Arons, 1998; Atoyan, 1999). The nebula’s emission may be modelled as a function of the particle injection spectrum related to the spin down energy of the pulsar, yet the exact processes which link the thermalising pulsar wind to the observed synchrotron emission are not clear (Reynolds & Chevalier, 1984), neither is our understanding of the particle acceleration processes within the pulsar wind in the first place (Gallant & Arons, 1994; Lou, 1993).

Another ‘young’ pulsar/SNR/X-ray plerion association that provides a working laboratory with which to test our understanding of such interactions following on from the Crab is that of the young radio, X-ray and γ -ray pulsar PSR B1951+32 associated with the CTB 80 SNR. Early radio and X-ray observations noted a central plerion/spectrally flat region to the SW of the SNR, within which PSR B1951+32 was detected, located within a concentration of nebular emission towards one edge of the flat spectral region (e.g. Strom et al. 1984). The association is valid based on this clear interaction between pulsar and remnant, with similar pulsar canonical age (107 kyr) and dynamically derived SNR age ($9.6 \times 10^4 d_{2.5 kpc}$).

Strom (1987) performed a detailed survey of this central flat region with the VLA at various frequencies and baselines, all yielding maps with resolutions $\sim 1''$, and recent surveys using the WSRT at 6 cm (Strom & Stappers, 2000) have indicated considerable complexity within the spectrally flat core. Strom was the first to comment on the ‘hot spot’, located to the SW of the pulsar, suggesting that it was likely a consequence of the pulsar wind interacting with the remnant and creating a ‘wisp’ like structure similar to that observed in close proximity to the Crab pulsar.

In contrast to the young Crab, it appears that the older PSR B1951+32 has caught up with its expanding remnant, resulting in the observed complex multiwavelength emission.

As such, it represents an extremely interesting stage in the life cycle of a pulsar, when the neutron star penetrates and interacts with the remnant/swept up ISM region. Precisely what radiation gets emitted, and where, will define the constraints to any subsequent modelling efforts.

Moon et al. (2004) have recently reported an optical/X-ray analysis of the system using archival HST and Chandra data, in addition to new ground based optical and IR observations. The Chandra data clearly shows a cometary pulsar wind nebula which appears to be confined by a bow shock produced by the high velocity motion of the pulsar, which corresponds to Strom's previously defined radio 'hot spot'. Optical/IR photometry have also indicated the presence of a synchrotron 'knot', as originally reported by Hester (2000) embedded within the cometary head observed by Chandra. Previous attempts to isolate putative optical counterparts to PSR B1951+32 have been concentrated around this structure, which is believed to be closely related to the pulsar - thus far two candidates have been proposed which are within the VLA error ellipse (Butler et al. 2002). Moon et al. (2004), based on their analysis, argue that only one is likely, and even then it is generally agreed that the 'point source' involved may well be a background star or non-uniformity in the knot itself.

The key to resolving many of the outstanding aspects of the the system's multiwavelength geometry is a rigorous astrometric reference frame. In this short letter we report a 16 hour L band observation with the MERLIN radio interferometer. Both objects were resolved at a resolution of 150 mas, and despite the relatively low signal to noise of the extended emission associated with the shock front, we have been able to re-examine existing multiwavelength data using the MERLIN data as the astrometric reference.

2. Observations & Data Analysis

On January 19th 2002, a 16 hour L-band MERLIN¹ observation (without the Lovell Telescope) was performed on the central spectrally 'flat' region centred on PSR B1951+32. The phase calibrator used was 1951+355, whose position is tied into the ICRF, with a positional accuracy of < 0.5 mas. The correlator was configured to operate at 1658 MHz with a total bandwidth of 16 MHz on 32 channels. The data was processed and analysed within the AIPS environment. Initial maps showed contamination from a bright off-axis radio source. This was identified as MG3 J195211+3248 ($\alpha \sim 19:52:15.7811$, $\delta \sim 32:49:36.299$),

¹MERLIN, a UK National Facility operated by the University of Manchester at Jodrell Bank Observatory on behalf of PPARC

a symmetric double radio galaxy, with a measured flux of ~ 80 mJy. Its contribution was subsequently CLEANed out.

2.1. Imaging the Pulsar and Environs

The pulsar is clearly evident in figure 1, and its position as obtained during this observation with MERLIN is determined to be $\alpha \sim 19:52:58.204$ ($\pm 0.002''$), $\delta \sim +32:52:40.531$ ($\pm 0.025''$) (2452294 JD). PSR B1951+32 was detected as a point source in this observation, and there was no evidence for scatter-broadening. There is also a significant ($\sim 4.5\sigma$) detection of a structure within the anticipated ‘hot spot’ some $3''$ SW of the pulsar, of approximate dimensions $2.5'' \times 0.75''$, with the pulsar’s motion approximately bisecting the observed emission.

Despite being relatively weak in terms of signal to noise, we note that this ‘bead-like’ arc of emission corresponds with lower-resolution data obtained with the VLA². We estimate that an excess flux density of ~ 2.84 mJy along the narrow (1-2 beams in width) linear feature on top of the larger ($\sim 1''$) structure. This is similar to our determination of ~ 2.59 mJy of excess flux relative to the shell from the complementary VLA data. Whilst the errors of these measurements is likely to be larger than their difference, this suggests that the shock structure is not over resolved in the MERLIN observations, and that the actual emission region is spatially limited. Thus, whilst we are confident that MERLIN has resolved fine-structure within the ‘hot spot’ observed previously, although given the low signal to noise ratio, one must be cautious to avoid over-analysing the MERLIN data.

2.2. The Optical Synchrotron Knot

The optical knot, first identified by Hester (2000) in the original HST F547M observations, can now be placed in its correct astrometric context given this MERLIN dataset. To do this, we must astrometrically calibrate the HST image to a significantly better degree than what is provided via the GSC. This is done by referencing the HST data to the 2MASS Point Source Catalog. The limiting astrometric accuracy of the latter is ~ 100 - 150 mas (1 sigma) relative to the Hipparcos/Tycho coordinate system, which realizes the ICRS for optical data.

²The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

The image was astrometrically calibrated to the ICRS via the following fitting process. 40 stars common to both the WFPC2 and the 2MASS Point Source Catalog were identified, the former extracted as pixel coordinates using DAOPHOT and were then corrected for the known geometric distortions. These pixel coordinates are each internally accurate to <<100 mas, since the stars have a PSF FWHM of ~ 125 mas.

The initial matching was based on the pipeline World Coordinate System (WCS) of the HST image. The first fit showed that this WCS was approx. 500 mas systematically in error. A second matching and fitting iteration was performed, 2nd-order CCMAP fits used a 2-sigma rejection cutoff to remove input stars of lower astrometric fidelity. The final iteration resulted in 9 of the 40 input stars being rejected and 31 stars surviving to define the fit for a new WCS solution, with a final fit rms of 105 mas in RA and 101 mas in Dec. This refined WCS was then written into the header of the HST image.

Comparison with the MERLIN astrometry is thus performed purely by reference to this WCS. Therefore, we stress that the radio-optical comparison is in no way dependent on any dubious procedure such as trying to tie together one or more features which might appear to be in common to the HST and MERLIN images. Their respective calibrations to the ICRS were performed via completely independent and robust means, and are anchored within the WCS schema.

In figure 2 we overlay the 2MASS corrected HST image on our L band MERLIN map, using the WCS header information in both cases. Hester’s knot is apparent in the field centre. Morphologically, the knot resembles a teardrop-like structure, of dimensions $0.8'' \times 1.3''$. We also show the position of the radio pulsar and the shock front. Astrometric integration of the MERLIN data yields an overall accuracy in registering the optical to the radio frame of ~ 105 mas. Within the combined astrometric errors as defined by the WCS solutions, this alignment makes a powerful case for the pulsar and Hester’s nebula to be associated. The pulsar is located at the lower south-west extent of the optical knot region. Knowing the approximate direction of the pulsar’s motion, this suggests that the knot’s observed optical emission is a consequence of shocked pulsar wind material and/or shocked nebular material during the transit of PSR B1951+32.

Ram pressure balance between relativistic pulsar winds and the ambient medium may be represented as $\rho_a v_{\text{psr}}^2 \sim \dot{E}/4\pi\Omega c r_s^2$, with ρ_a the ambient medium density, \dot{E} the pulsar’s spin-down energy, the $4\pi\Omega$ term the solid angle of the pulsar wind flow and r_s the stagnation radius - c being the speed of light. Typically in these treatments, the ram balance implies equipartition of particle and magnetic field pressure at the shock front, and this allows one to express the local magnetic field as $B_{eq}(\mu G) \sim 50(n_H/\text{cm}^3)^{1/2}(v_{\text{psr}}/100\text{km s}^{-1})$, or equivalently $B_{eq}(\mu G) \sim 200\Omega^{-1/2}(\dot{E}/10^{36}\text{erg s}^{-1})^{1/2}(r_s/0.01\text{pc}^{-1})$ with n_H the hydrogen number

density.

The recent VLA observations of Migliazzo et al. (2002) have determined $v_{psr} = 240$ km s $^{-1}$. Chandra data imply $r_s = 0.03$ pc (or 3" at 2 kpc) and $\dot{E} = 3.7 \times 10^{36}$ ergs s $^{-1}$. Assuming $\Omega < 1$, Moon et al. (2004) argue that $B_{eq} > 100$ μ G. These authors indicate that this result correlates with earlier Hester & Kulkarni (1989) results of a pre-shock n_H of 50 cm $^{-3}$ and $B_{eq} \sim 600$ μ G. Moon et al. (2004) then argue that if one assumes $B > 100$ μ G in the X-ray nebula, then the synchrotron cooling time of these X-ray photons is $t_{sync} \sim 40E_{keV}^{-1/2}(B/100\mu G)^{-3/2}$ or < 40 yrs. Given the nebula's spatial extent along the pulsar's axis of motion of $\sim 20''$, and PSR B1951+32's proper motion of ~ 25 mas/yr, this points towards the nebulae being constantly replenished by the pulsar wind, certainly in X-rays.

Optically, the knot's length of $\approx 1.3''$ and the pulsar's proper motion suggest a lifetime of ~ 50 years. Assuming the knot's emission is a consequence of 'cooling' synchrotron particles, one can use this crossing time as the cooling time, and the energy of these optical photons to constrain the previous equation to yield a value for B_{eq} , which comes to ~ 600 μ G, not inconsistent with the previous studies.

However, this analysis suggests that the observed optical emission is entirely explicable as synchrotron emission from the pulsar wind particles left behind after passage of the pulsar - without the requirement of particle replenishment by the same pulsar wind. Moon et al. 2004 used particle replenishment to justify their analysis of the Chandra data. For replenishment to be valid (Kaspi et al. 2001), the freshly shocked wind particles must be continuously fed 'backwards' with a velocity that is high enough given their cooling times. Given the estimated cooling times and dimensions of the optical knot, an X-ray knot associated with it would have a particle cooling time of ~ 0.3 to 9 years, with corresponding particle flow velocities of ~ 185 - 260 to km s $^{-1}$ (optical) and 1.5×10^3 to 5×10^4 km s $^{-1}$ (X-ray).

An alternative interpretation is that the observed optical synchrotron knot is a consequence of quasi-stationary shock structures in the pulsar wind outflow behind the pulsar (Lou 1998). At various spin latitudes, reverse fast MHD shocks can appear quasistationary when their propagation speeds relative to the pulsar wind are comparable to the relativistic outflow. The most likely source of disturbances which explain why these wisps and knots appear where they are observed are slightly inhomogeneous wind streams emanating from the rapidly spinning pulsar. A slower wind stream will eventually be caught up by a faster wind stream to trigger forward and reverse fast MHD shock waves in the distant pulsar wind.

Enhanced synchrotron emission is expected from these knots due to the pitch-angle scattering of MHD shock-energised relativistic particles. There are various mechanisms available

to energise particles to high energies from plasma turbulence, from both the forward and reverse fast relativistic MHD shocks themselves as well as magnetic reconnection in the pulsar wind. Collectively, they strongly suggest the likelihood of a dynamic component to this optical knot.

Considering that PSR B1951+32 possesses an estimated transverse velocity of ~ 240 km s $^{-1}$, a counter knot may be ‘smothered’ by the bow shock formed by the pulsar’s passage towards the SW of the remnant. At the bow shock itself injected particles from the pulsar wind are advected behind the pulsar while some of the particles diffuse across the bow shock and into the shell of the SNR thereby rejuvenating the shells emission (van der Swaluw et al. 2002, Shull et. al 1989), which we see to the south-west of this remnant. Therefore the MHD wind streams may be advected away before they have an opportunity to interact, and therefore do not form a knot in the scenario proposed by Lou (1998). Taking into account recent simulations (Buccaniti 2002, Gaensler et al. 2004), the knot seems to lie in the subsonic region that exists behind the pulsar and it is surrounded by the supersonic region created by the back flowing material from the bow-shock. At the interface between these two regions there may exist shearing forces which may explain the asymmetry of the optical knot which is evident in figure 2.

2.3. Implications for Proposed Optical Counterparts to PSR B1951+32

There are strong grounds for the detection of an optical counterpart to PSR B1951+32, based on empirically derived relationships between other known optical pulsars (Shearer & Golden, 2001), and also on the fact the pulsar is a known X-ray and putative γ -ray pulsar. A previous analysis of this same HST data by Butler et al. (2002) suggested two potential optical counterparts which were coincident with the best reported VLA astrometry at that time - one a clear point source to the SW of the knot, the other embedded within the knot towards its upper NW edge. Moon et al. (2004) state that the former counterpart does not satisfy more rigorous astrometry, and propose that the latter is the only remaining candidate, albeit with the reasonable caveat that this latter source may be a background star or a transient localised emission region within the knot - a point also made by Butler et al. (2002). Our MERLIN astrometry rules out any association between it and the pulsar. However, it is reasonable to consider the possibility that the proposed counterpart is (was?) a non-uniformity within the synchrotron nebula. This would in turn support the idea that the optical structure we observe is a direct consequence of the pulsar wind outflow, and again argues the case for the knot to be a dynamically evolving structure.

3. Conclusions

We report the first high resolution radio observation of the inner PSR B1951+32 plerion using MERLIN at L band. We have resolved both the pulsar and apparent fine structure within the ‘hot spot’ identified at lower resolution and believed to be a consequence of the pulsar wind interacting with swept up ISM/SNR material.

We have used our MERLIN data to register the astrometrically corrected archival HST observations of the field. Combined, these data indicate that the previously identified optical ‘knot’ of synchrotron emission extends behind the pulsar, along a line that bisects the shock front emission. The dimensions of the optical knot and the VLA determined proper motion argue for a synchrotron cooling time that is consistent with particle replenishment from the pulsar wind.

The formation of the knot can also be attributed to the mechanisms outlined in Lou (1998) with the interaction of MHD wind streams, whilst the knot’s luminosity can be maintained by particle injection from the pulsar wind. Variations in the knot’s luminosity and morphology are anticipated as successive quasi-periodic disturbances emanate from the pulsar. This being so it argues for a fundamentally dynamical nature to the observed synchrotron knot which may only be really discernible using future HST or ground-based adaptive optics observations.

Finally, the MERLIN data definitively rules out the putative optical counterparts to PSR B1951+32 suggested by Butler et al. (2002) and Moon et al. (2004), and provides an unambiguous error box with which to assist future high time resolution searches.

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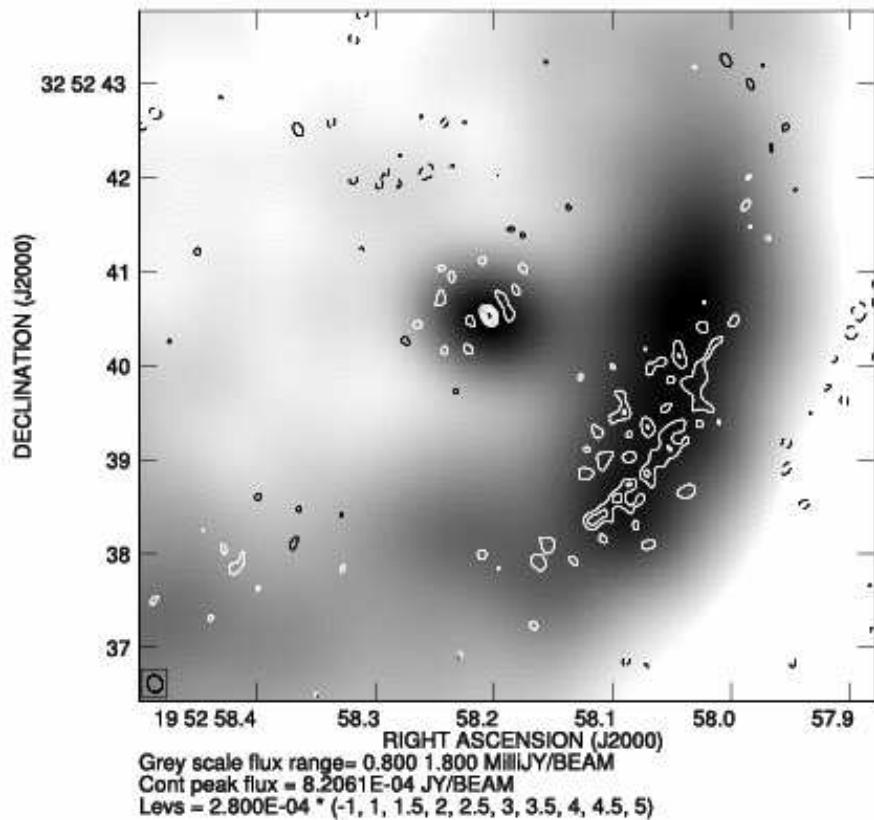


Fig. 1.— VLA grey-scale map with superimposed MERLIN L band contour map. The pulsar is clearly evident in the image centre as both a VLA and MERLIN point source. The MERLIN resolved shock-structure is to the SW of the pulsar, coincident with the poorer resolution VLA data, which was obtained in July 2003 in the A configuration. The rms noise level for the MERLIN data is 1.0×10^{-4} Jy/beam, and natural weighting was used in its analysis.

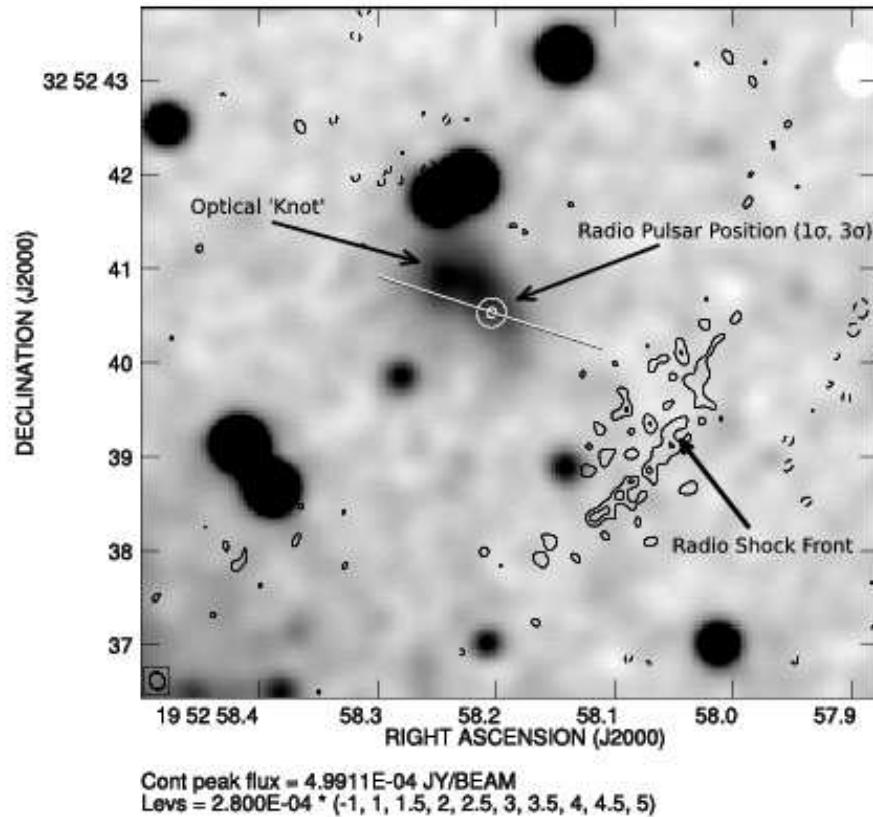


Fig. 2.— Smoothed inverse grey-scale HST F547M image of the central region, showing the ‘teardrop’ like optical synchrotron knot as originally marked out by Hester (2000). The white ellipses in the centre show the 1 and 3σ positions of the radio pulsar with respect to the optical frame as defined by the WCS. The black contours show the MERLIN map (the pulsar has been removed for clarity.) The white line shows the proper motion of the pulsar over a 100yr time frame. (from Migliazzo et al. (2002).)